Comparison of model surface currents and drifter data from the Grand Banks

Ewa Dunlap, Charles C.L. Tang and C. K. Wang

Ocean Sciences Division
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

2004

Canadian Technical Report of Hydrography and Ocean Sciences 236

Fisheries and Oceans Canada | Pêches et Océans Canada

Canada

Canadian Technical Report of Hydrography and Ocean Sciences

Technical reports contain scientific and technical information of a type that represents a contribution to existing knowledge but which is not normally found in the primary literature. The subject matter is generally related to programs and interests of the Oceans and Science sectors of Fisheries and Oceans Canada.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page. Out-of-stock reports will be supplied for a fee by commercial agents.

Regional and headquarters establishments of Ocean Science and Surveys ceased publication of their various report series as of December 1981. A complete listing of these publications and the last number issued under each title are published in the *Canadian Journal of Fisheries and Aquatic Sciences*, Volume 38: Index to Publications 1981. The current series began with Report Number 1 in January 1982.

Rapport technique canadien sur l'hydrographie et les sciences océaniques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles mais que l'on ne trouve pas normalement dans les revues scientifiques. Le sujet est généralement rattaché aux programmes et intérêts des secteurs des Océans et des Sciences de Pêches et Océans Canada.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page de titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

Les établissements de l'ancien secteur des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports en décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du rapport numéro 1 en janvier 1982.

104-03732/

Canadian Technical Report of Hydrography and Ocean Sciences 236

2004

Comparison of model surface currents and drifter data from the Grand Banks

by

Ewa Dunlap, Charles C.L. Tang and C. K. Wang

Ocean Sciences Division
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

ACKNOWLEDGMENTS

This work was supported by Canadian Coast Guard's New SAR Initiatives Fund (NIF) under the project "Ingestion of Grand Banks surface current data into CANSARP" (ID 2002038), and Program for Energy Research and Development (PERD). The authors wish to thank Jean Meillette, Katherine MacIntyre and Ron Dawson of Canadian Coast Guard College for collaboration and for providing drifter data for this project. Peter Smith coordinated the work and assisted in the planning of the project.

© Her Majesty the Queen in Right of Canada, 2004
Cat. No: 97-18/236E ISSN:0711-6764

Correct citation for this publication:

Dunlap E., C.C.L. Tang and C. K. Wang. 2004. Comparison of model surface currents and drifter data from the Grand Banks. Can. Tech. Rep. Hydrog. Ocean Sci., No. 236: vi + 28pp.

TABLE OF CONTENTS

PAGE

ACKNOWLEGEMENTS II

TABLE OF CONTENTS III

LIST OF FIGURES IV

LIST OF TABLES V

ABSTRACT VI

1.0 INTRODUCTION 1

2.0 OBSERVATIONAL DATA 3

2.1 Data description 3

2.1 Data processing 5

3.0 ICE-OCEAN FORECAST MODEL 8

3.1 Model description 8

3.2 Ocean surface current 9

3.2 Stokes drift 10

4.0 OCEAN FORCAST VALIDATION RESULTS 15

4.1 Comparison with the empirical model 15

4.2 Comparison of time series 18

4.3 Comparison of trajectories 21

5.0 CONCLUSIONS AND RECOMMENDATIONS 27

6.0 REFERENCES 28

LIST OF FIGURES

PAGE

Figure 1 SLDMB drifter trajectories 4

Figure 2. Ocean depth along drifter tracks 5

Figure 3. Sample time series of measured drifter positions and velocit components..... 6

Figure 4. Sample time series of drifter positions and velocity components after processing. 7

Figure 5. Labrador model domain and bathymetry (left) and sigma levels (right). The Grand Banks sub-domain is indicated by the broken black lines. 9

Figure 6. The effect of surface current definition on 48 hour trajectories 10

Figure 7. 16 October 2002. 48 hour surface current trajectory from model (blue) without Stokes drift (top) and including Stokes drift (bottom). The observed drifter trajectories are plotted in red. 12

Figure 8. 29 October 2002. 48 hour surface current trajectories from model (blue) without Stokes drift (top) and including Stokes drift (bottom).). The observed drifter trajectories are plotted in red. 13

Figure 9. Sample CMC wind speeds at synoptic times T00 and T24 14

Figure 10. Comparison between POM (top) and simple wind based model (bottom) trajectories (blue). The observed drifter trajectories are plotted in red. 16

Figure 11. Comparison of the observed and modeled 2-day trajectory structure for two selected samples. 17

Figure 12. Comparison of drifter velocity component U (ms^{-1}) with modeled current velocity component U (ms^{-1}) at drifter locations 19

Figure 13. Comparison of drifter velocity component V (ms^{-1}) with modeled current velocity component V (ms^{-1}) at drifter locations 20

Figure 14. Diagram illustrating the distance (top) and separation (bottom) after 1 and 2 day 22

Figure 15. Scatter diagrams of the end points distance after 1 day (green dots) and 2 days (blue dots). The separation between the observed and modeled trajectories (indicated with vertical lines) is scaled by the factor 0.2. N=132 points. The red lines are linear fits of the data points. 23

LIST OF TABLES

PAGE

Table 1 Separation mean ± standard deviation 24

Table 2 Correlation coefficient and scatter index of the trajectory distance 25

ABSTRACT

Dunlap E., C.C.L. Tang and C. K. Wang. 2004. Comparison of model surface currents and drifter data from the Grand Banks. Can. Tech. Rep. Hydrog. Ocean Sci., No. 236: vi + 28 pp.

Data from four surface drifters deployed on the Grand Banks in October-November 2002 by Canadian Coast Guard were processed and analyzed to obtain surface currents. The velocity time series and drifter trajectories were simulated using the Princeton Ocean Model (POM), the Stokes drift computed from an empirical equation, and a simple empirical model for surface current. A comparison of the model results with data indicates that the best simulation is obtained from POM with the Stokes drift correction. Sources of errors and improvements of the models are discussed. Recommendations for further studies are given.

RESUME

Dunlap E., C.C.L. Tang and C. K. Wang. 2004. Comparison of model surface currents and drifter data from the Grand Banks. Can. Tech. Rep. Hydrog. Ocean Sci., No. 236: vi + 28pp.

On a traité et analysé des données provenant de quatre dériveurs de surface mouillés sur les Grands Bancs en octobre-novembre 2002 par la Garde côtière canadienne pour connaître les courants de surface. La série chronologique sur la vitesse des courants et les trajectoires des dériveurs ont été simulées à l'aide du modèle Princeton Ocean (POM), de la dérive de Stokes calculée d'après une équation empirique et d'un modèle empirique simple de courants de surface. Il ressort d'une comparaison des résultats que la meilleure simulation est celle obtenue à l'aide du POM, après correction d'après la dérive de Stockes. Le présent document traite des sources d'erreur et des améliorations des modèles. Il contient aussi des recommandations pour de plus amples études.

1.0 INTRODUCTION

Marine search-and-rescue (SAR) operations require reliable information on surface currents. They are important for the determination of search area in SAR planning. A primary planning tool used by Canadian Coast Guard is CANSARP (Canadian Search and Rescue Planning), a computer software package to establish the drift of SAR targets. For most offshore areas, CANSARP utilizes archived ocean current observations to predict surface current. The grid spacing for such regions varies from 10 to 36 kilometers. In coastal and inshore areas, CANSARP utilizes tidal models, some of which are coupled to observed winds and variable river flows. The resolution of tidal grids is much finer and varies from 1.6 to 21.3 km.

Archived data represent mean current averaged over a long periods from days to months. These long-term averages do not necessarily describe accurately the actual current conditions in a SAR situation. Currents will typically be significantly different from the mean current due to wind forcing, tides and other factors.

In CANSARP, the wind response of the surface current in offshore areas is calculated by one of two ways. The first and fastest method is to use an empirical relationship which sets the surface current to 3.3% of the wind speed and 20° to the right of the wind direction. The winds used by CANSARP are the Canadian Meteorological Center (CMC) operational 48 hour forecast winds at 6 hourly synoptic times. Alternatively, the current values based upon an on-scene observation, e.g. from drifting marker buoys (DBM's) specially deployed for the purpose, or from other reliable sources can be input to CANSARP.

Real time and near real time data would greatly enhance CANSARP's ability to accurately predict the drift of search subjects. The objective of this project is to provide and test a new surface current data set for the input to CANSARP. The surface currents are produced by the BIO Ice-Ocean Forecasting System. The area where the data will be used, the Grand Banks of Newfoundland, is an important marine zone of the east coast with oil production and fishing.

The BIO Ice-Ocean Forecasting System is an automated system developed by scientists at Bedford Institute of Oceanography/ DFO (http://www.mar.dfo-mpo.gc.ca/science/ocean /icemodel/ice_ocean_forecast.html). It generates one and two-day forecasts of surface currents and other ocean variables for the Grand Banks every day using advanced computer models.

The BIO system executes a coupled ice-ocean model and a wave mode. The models cover the Grand Banks, Newfoundland and Labrador shelf regions and the Labrador Sea. Tidal constants from a Grand Banks tide model are used to compute tidal currents and sea level, which are then added to the output from the coupled ice-ocean model to obtain the total surface currents on the Grand Banks. The technical details are given at the above BIO website. Model improvements are being carried out at BIO on an ongoing basis and there are plans to extend the surface currents forecast to other areas in the future.

The objective of this report is to evaluate the accuracy of the BIO forecast surface currents using data collected by four surface drifters deployed over the Grand Banks by Canadian Coast Guard College in October 2002.

This study suggests that the effects of waves should be considered in surface current forecasts. In the presence of waves there is an additional contribution to surface current (the Stokes drift) in the direction of wave propagation, which is not considered in traditional ocean models. The results of BIO model that includes Stokes drift have been shown to give better predications than those using an empirical ocean current model based on wind speed and direction only.

This report is organized as follows:

- Observational data and their processing are described in Section 2
- Ocean forecast data are described in Section 3
- The results of ocean forecast validation are presented in Section 4
- A discussion of the model results are given in Section 5
- Conclusions and the recommendations for future work are given in Section 6

2.0 OBSERVATIONAL DATA

2.1 Data description

For the purpose of this study, four surface drifters were deployed by Canadian Coast Guard College at Grand Banks during 7-9 October 2002. These were Self Locating Datum Marker Buoy (SLDMB) in "Person in Water" mode (i.e minimal leeway) manufactured by Seimac (http://www.seimac.com/).

The SLDMB is a tool used in marine rescue operations. The buoy is an air launchable, self contained marker buoy. It is designed to drift with wind and current in one of two pre-selected configurations.: (1) Person in Water (PIW) and (2) Liferaft . In the PIW mode, the buoy is designed to drift like a person in a survival suit. The buoy, upon entering the water, deploys both a floatation bag unit and a surface drogue. In the Liferaft Configuration mode the buoy drifts like a four-man liferaft similar to the PIW mode but without the drogue system. In either configuration a float unit is deployed which contains an automatic inflation device, batteries, a satellite transmitter, a GPS navigation system, and a water temperature sensor. The SLDMB unit has an operational life of 5 days. At the end of life, a scuttling device causes the float bag to deflate, sinking the unit. During this experiment the SLDMB drifters were transmitting for a period of time exceeding their operational lifetime and lasted from 11 to 48 days.

Data were transmitted via satellite at a rate of 3-4 fixes per hour. Drifter trajectories within the Grand Banks are shown in Figure 1. The GPS location accuracy is ± 100 m.

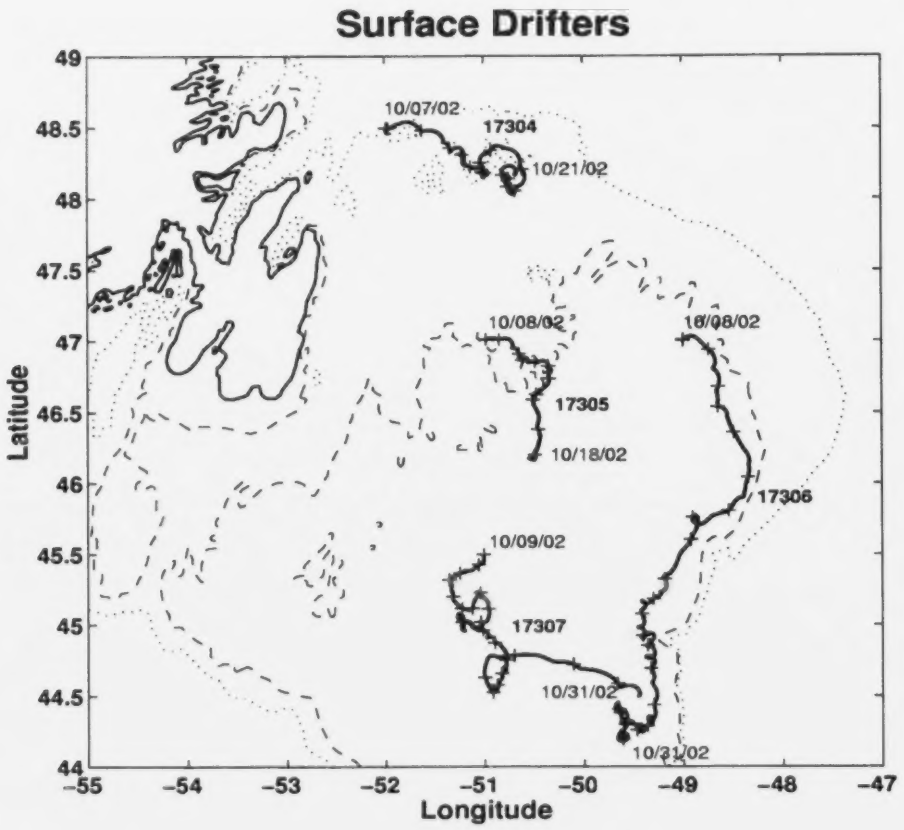


Figure 1 SLDMB drifter trajectories

The drifters were within the 2000-m isobath of the Grand Banks from 7 to 31, October 2002. Data outside Grand Banks were not used. Buoys were released in four locations chosen to provide good coverage of the area.

Drifter buoy 17304 was launched in the northern part of the Grand Banks (approximately on the 200 m isobath) and moved southeastward approximately 108 km. Drifter 17305 was launched farther south and moved southeastward along the 100-m isobath for about 6 days before turning south. The distance between trajectory end points is approximately 99 km. Drifter buoy 17306 was deployed farther east and followed the Labrador Current for about 314 km. The last buoy, 17307, was released in the centre of the shelf, moved southeastward about 167 km and remained in almost constant water depth of ~70 m.

The ocean depth (from a bathymetry data base) along the drifter tracks is shown in Figure 2.

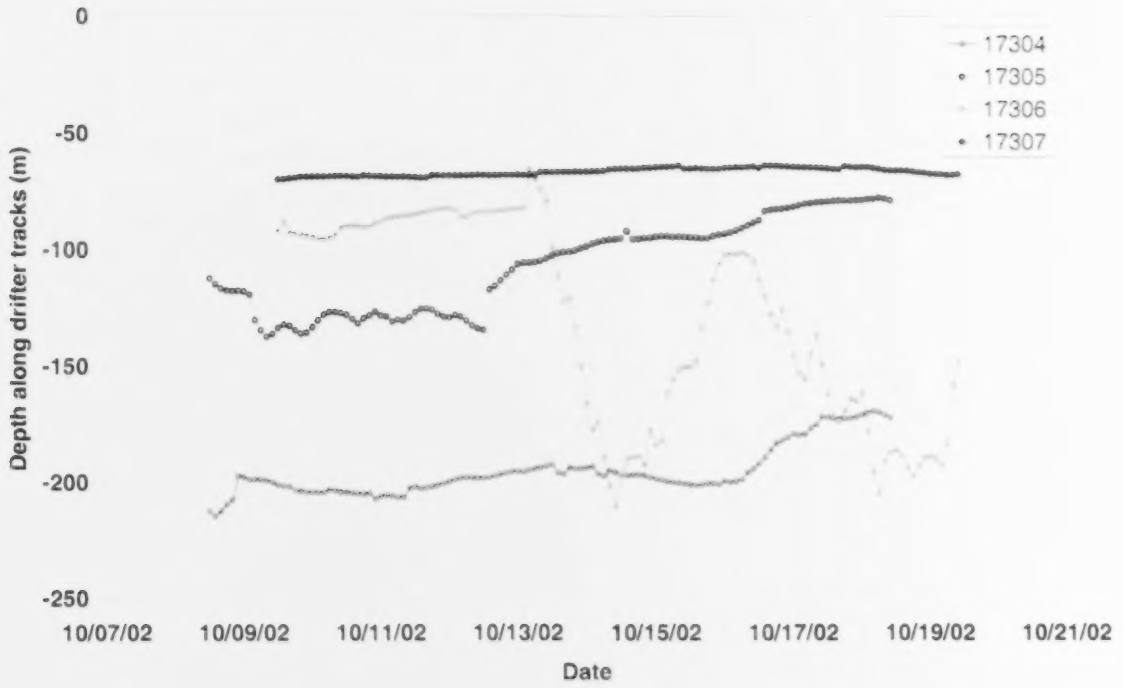


Figure 2. Ocean depth along drifter tracks

2.1 Data processing

Drifter data were downloaded from a Canadian Coast Guard College website. They were decoded using the SLDMB decoding program. Original data files contain records with the following eleven data fields:

ID day month year hour minite second latitude longitude speed direction

A sample of raw drifter position and velocity components data for 17304 is shown in Figure 3. Apparently, raw data must be further processed to remove instrumental and transmission errors. The raw position data were despiked manually. Hourly positions were generated using a second order polynomial fit with a window of 4 hours. Houly velocity were calculated from the coefficients of the polynomials. Despked and fitted drifter positions and velocity components for are given in Figure 4, respectively.

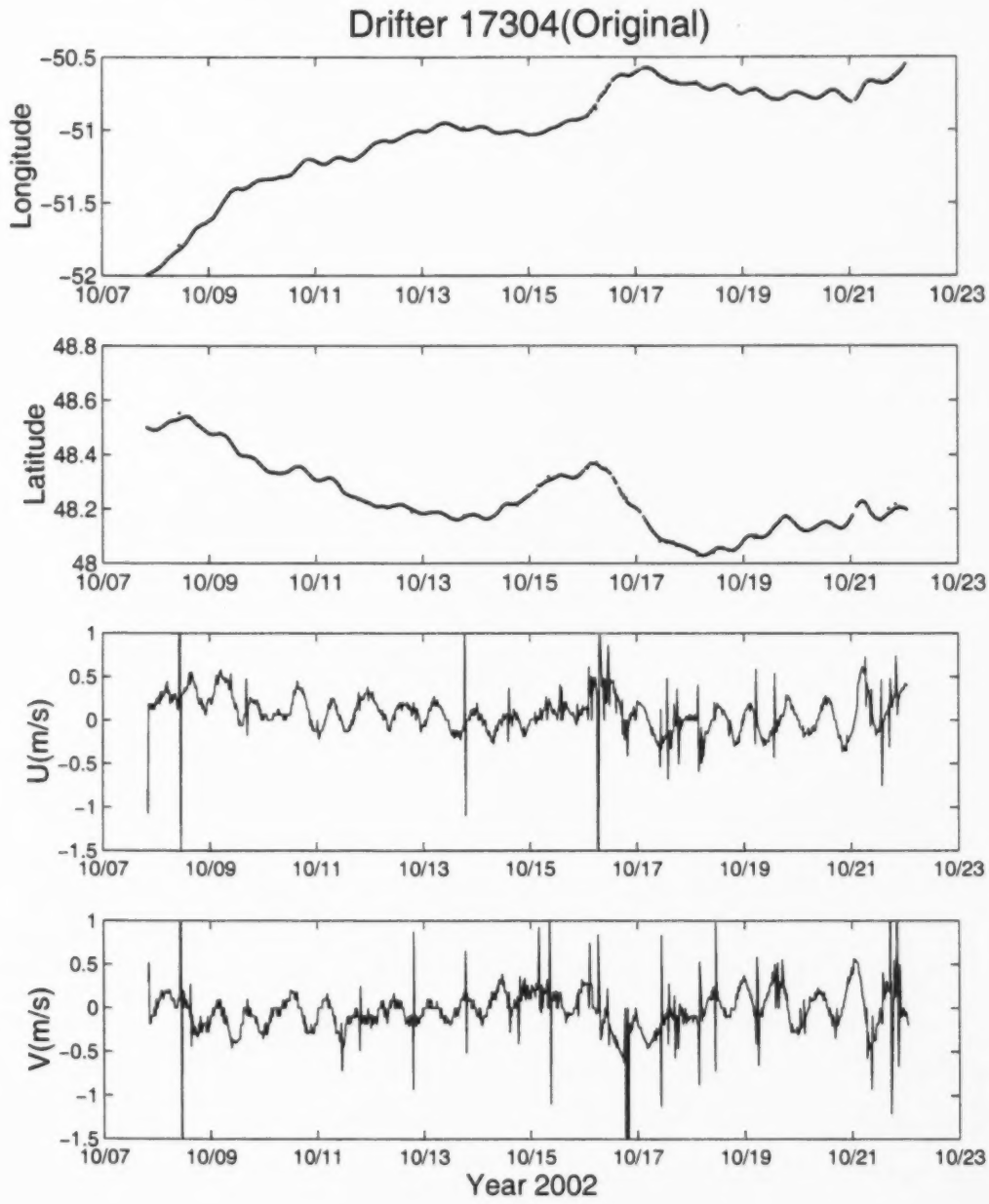


Figure 3. Sample time series of measured drifter positions and velocit components

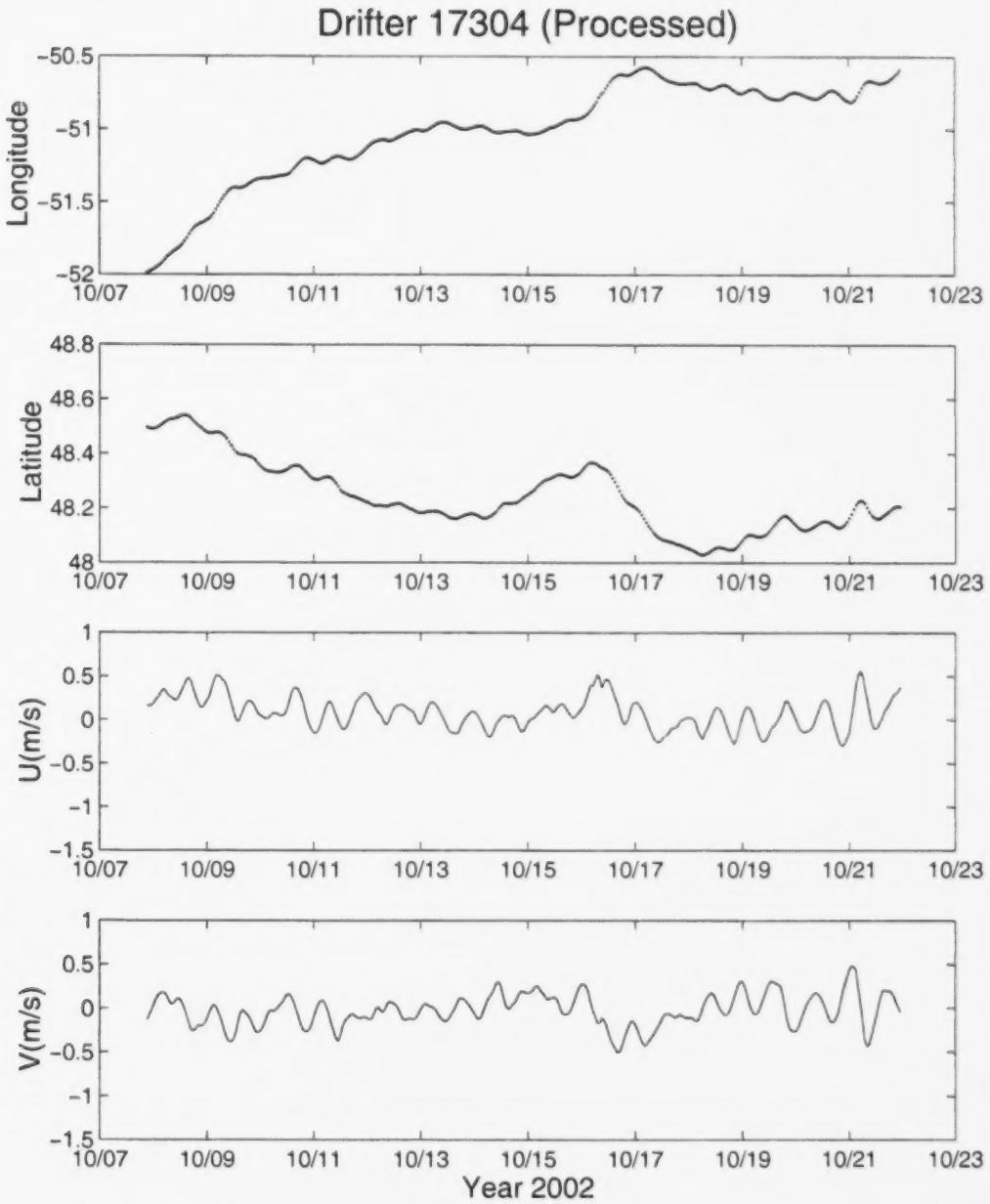


Figure 4. Sample time series of drifter positions and velocity components after processing

3.0 ICE-OCEAN FORECAST MODEL

3.1 Model description

The BIO ocean forecasting system - Ice-Ocean Forecasts for the East Coast of Canada (http://www.mar.dfo-mpo.gc.ca/science/ocean/icemodel/ice_ocean_forecast.html) produces 2-day forecasts of surface currents, waves, water levels and ice cover for eastern Canadian seaboard. The model used for ice-ocean forecasts is a coupled sea-ice model and Princeton Ocean Model (Yao *et al.*, 2000).

Princeton Ocean Model (Blumberg and Mellor, 1987; Mellor, 1996) is a primitive equations, sigma coordinate model. It contains an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients (Mellor and Yamada, 1982).

The forcings are six hourly surface winds, air temperature, dew point temperature, and cloud cover. On the open boundaries, temperature, salinity, sea surface elevation, volume transport are fixed for each season.

Forecast currents are generated on a (1/5° long × 1/6° lat) grid and at 16 variable sigma levels in the vertical. The Labrador model domain includes the Grand Banks, N.E. Newfoundland Shelf, Labrador Shelf and Labrador Sea. The internal model grid has ($N_{lon} \times N_{lat}$)=(130 × 156) grid points with the bottom left node located at (66W, 40N)

Tidal currents and sea levels for Grand Banks are computed separately for five principal constituents, M_2, S_2, N_2, K_1 and O_1 (Han, 2000). The Grand Banks subdomain has ($N_{lon} \times N_{lat}$)=(40 × 42) grid points with the bottom left node located at (55W, 42N).

The Labrador model domain and topography are shown in Figure 5 (left panel), in which the Grand Banks subdomain is indicated. All the results presented here are for the Grand Banks sub-domain, covering the area of (56° W to 47° W) × (42° N to 49° N). The sigma levels and the location of the current velocities on the vertical grid are shown in Figure 5 (right panel).

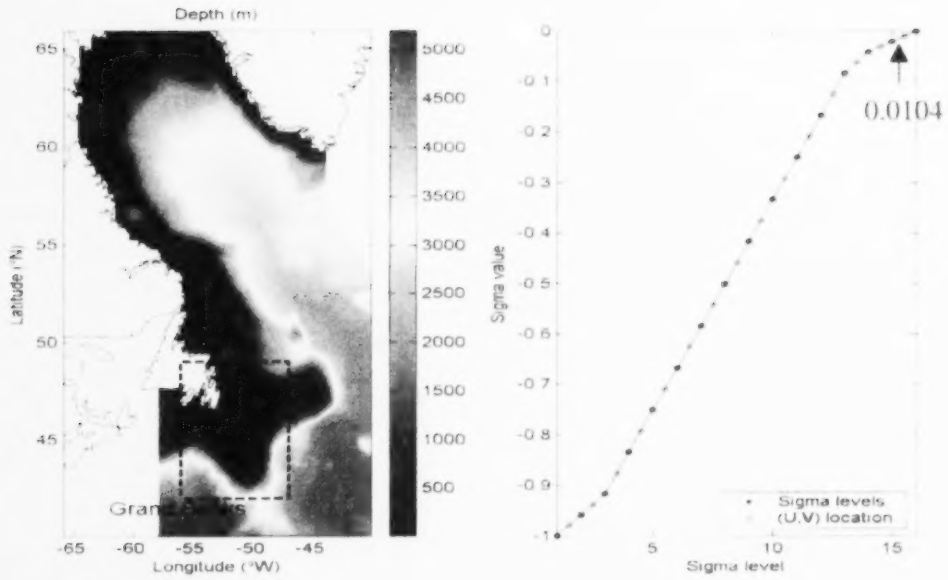


Figure 5. Labrador model domain and bathymetry (left) and sigma levels (right). The Grand Banks sub-domain is indicated by the broken black lines.

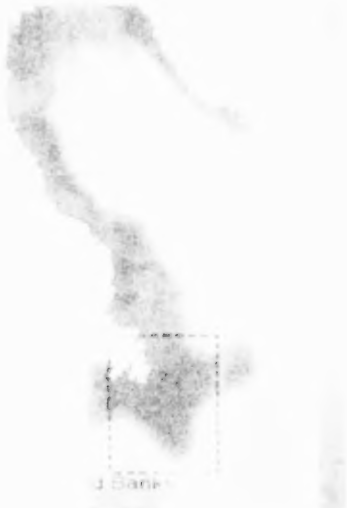
3.2 Ocean surface current

The 48-hour forecast model provides three-dimensional ocean current velocity fields every 2 hours. The forecast starts daily at noon. Based on the forecast data, the surface current velocity and corresponding trajectories were estimated for the comparison with the observed drifter trajectories.

Under low wind conditions the velocity field reflects the mean currents. The mean circulation is dominated by the Labrador Current, with flow along the 500 m isobath in th northeast Grand Banks, and continues south along the eastern shelf edge of the Grand Banks. In the interior of Grand Banks the mean currents are small.

In sigma models the velocity is defined in the centers of the vertical grid. Therefore the surface current velocity is undefined, as can be seen in see Figure 5 (right panel). In the Labrador model the velocity of the top sigma level is located below the surface at $z^{Top}_{(U,V)} = \eta - 0.0104 \cdot (H + \eta)$, where H is the water depth and η is the surface elevation.

Three different surface current estimates were computed. These included: (1) top level current, (2) current averaged within 10m from the surface, and (3) current averaged within 30m of the surface. For sigma levels within the predefined depth, the weighted average was computed



with the weights defined as a ratio of the corresponding sigma level thickness to the thickness of the averaged layer: When the thickness of the averaged layer increases, the coverage of the corresponding averaged surface current also increases.

Trajectories based on these three currents were compared as shown in Figure 6.

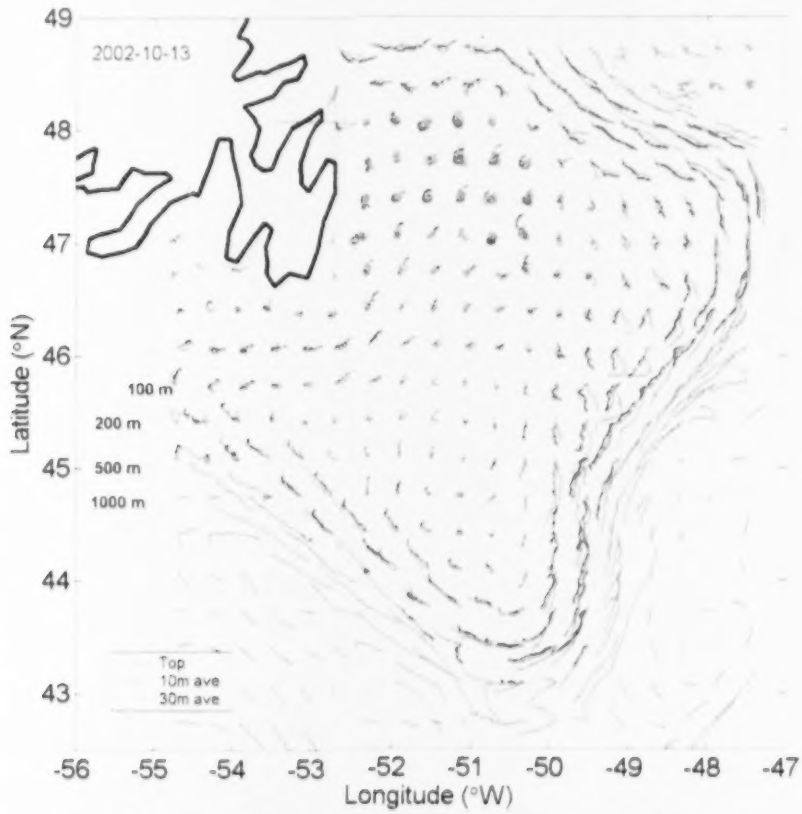


Figure 6. The effect of surface current definition on 48 hour trajectories

As expected, the top level velocities are larger than the averaged ones and over-predict surface currents. The differences between the trajectories based on 10 m and 30 m averaged currents are not large. However, the spatial coverage of the surface currents averaged over 30m allows for comparison of a larger number of data measured by the drifter 17306 within the Labrador current because the vertical grid spacing depends on water depth. Therefore, 30-m averaged surface currents are used in the following sections, unless indicated otherwise. A further discussion of the averge depth will be given in the Section 5.

3.2 Stokes drift

In POM and other ocean circulation models, wave effects are not considered. This is generally a

valid approximation for studies where the ocean surface effects are not the central interest. Perrie et al. (2003) shows that the wave-modified currents can exceed the standard Ekman current by 40% in rapidly developing intense storms. A large part of this increase in current velocity is due to the Stokes drift, which is the net displacement of surface water due to the orbital motion and nonlinear dynamics of surface waves.

The Stoke's drift can be parameterized by wind speed and fetch L as follows (Wu, 1983):

$$\vec{u} = 0.0186\left(g \cdot L \cdot \vec{w}_{10}^{-2}\right)^{0.03} \vec{w}_{10}$$

where:

$\vec{u}$ is the empirical wave induced surface current velocity

$\vec{w}_{10}$ is the wind velocity 10 m above the ocean surface

L is the fetch length

The Stokes drift is not sensitive to L. The drift velocity increases from 2% of wind speed for L = 100 m to 2.5% for = 100 km. We use a constant value of L = 10 km.

In order to show the effect of wave induced corrections, two cases are selected. In the first case (Figure 7) all drifters (indicated in red) are located within the model domain and winds are in the eastward direction with the maximum wind speed of 13.3 m s^{-1}. In the second case (Figure 8) winds are stronger than in first case, with the maximum wind speed of 22.2 m s^{-1} and the effect of the Stokes drift is very clearly visible. Only 2 drifters remained in the model domain at this time.

The green dots marked on the trajectories indicate the locations at the beginning of the forecast (T00) while the black dots show the trajectory point after 24 hours (T24). For clarity of the plots the trajectories are plotted every two grid points.

Wind fields corresponding to Figures 7 and 8 are given in Figure 9. Only the T00 and T24 hour winds, that correspond to green and black dots shown on the drifter trajectories, are plotted.

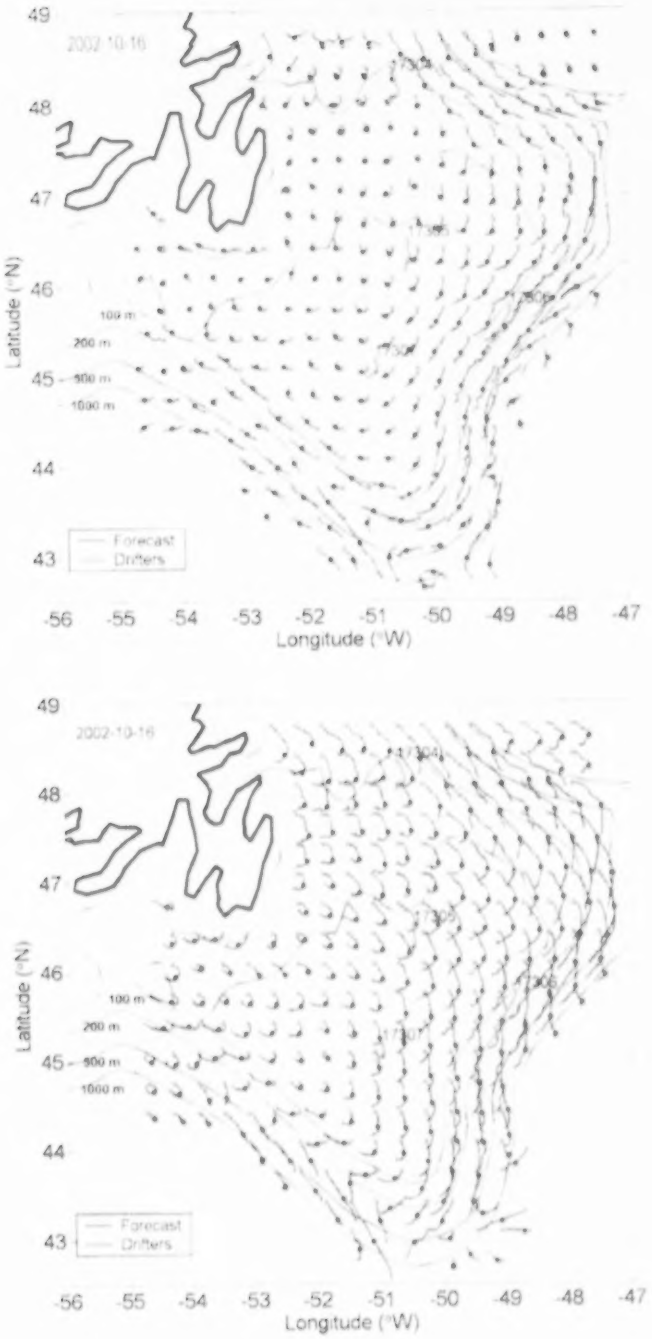


Figure 7. 16 October 2002. 48 hour surface current trajectory from model (blue) without Stokes drift (top) and including Stokes drift (bottom). The observed drifter trajectories are plotted in red.

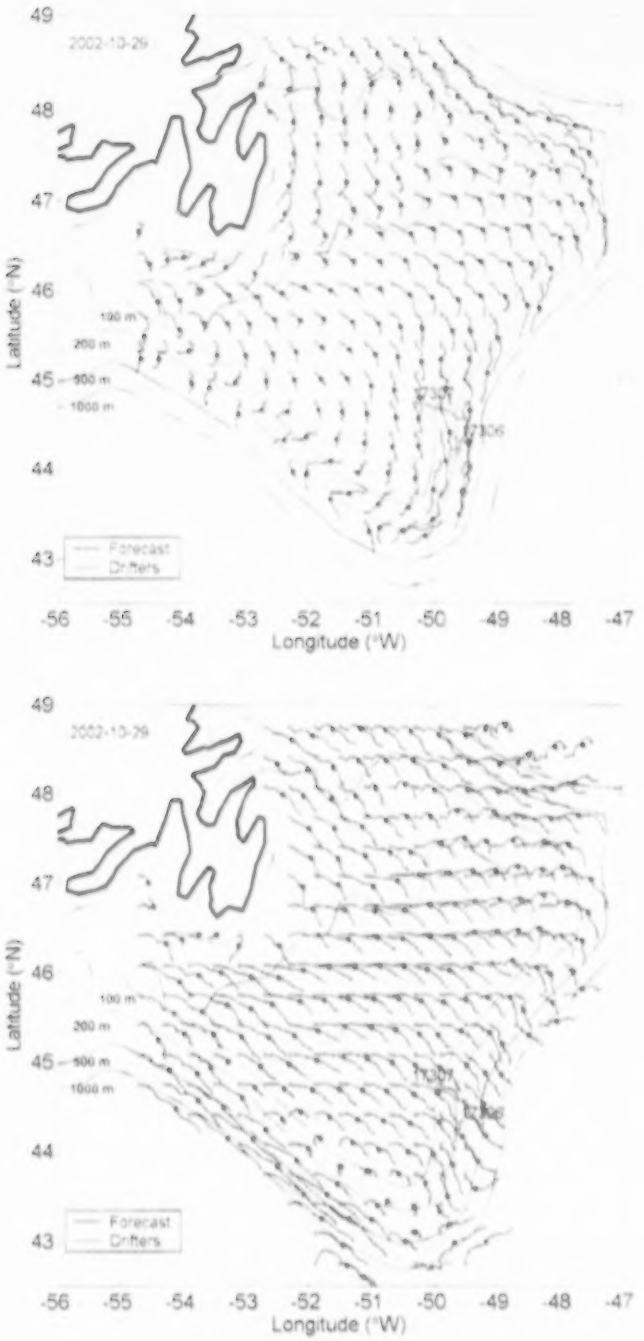


Figure 8. 29 October 2002. 48 hour surface current trajectories from model (blue) without Stokes drift (top) and including Stokes drift (bottom).). The observed drifter trajectories are plotted in red.

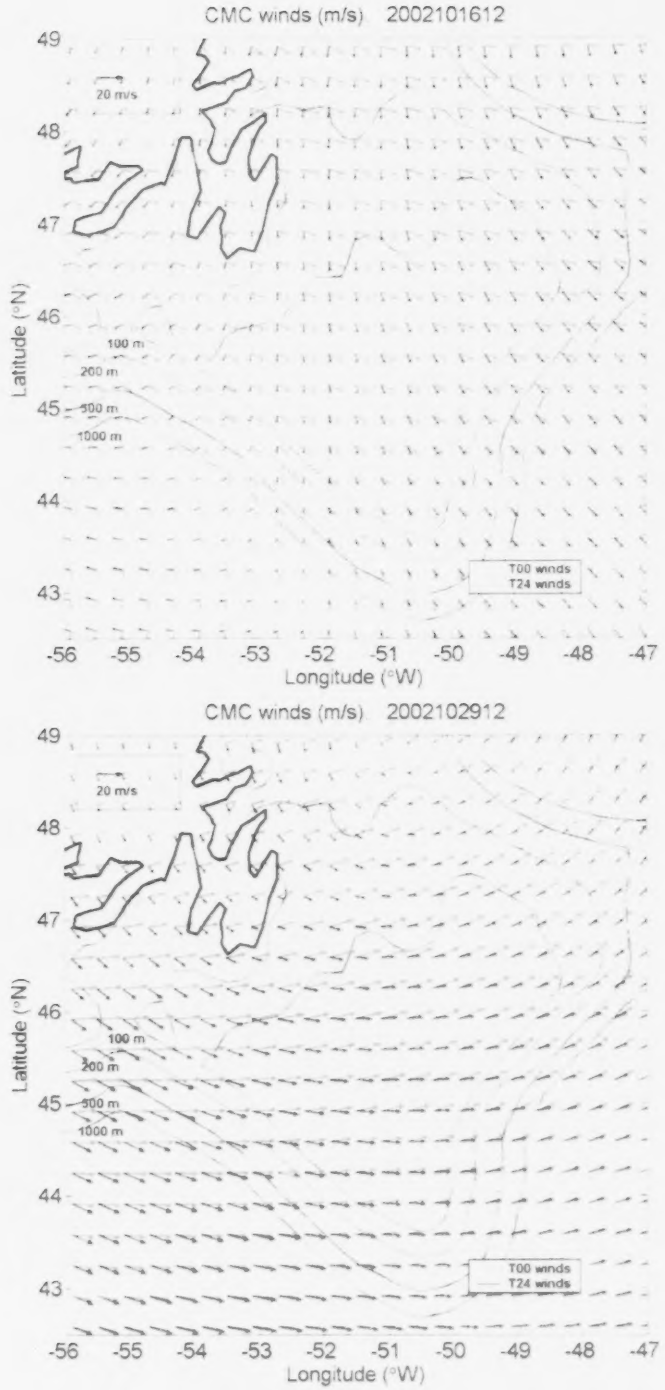


Figure 9. Sample CMC wind speeds at synoptic times T00 and T24

4.0 OCEAN FORCAST VALIDATION RESULTS

In this section forecast model results, with and without the Stokes drift, are compared with drifter observation and with predictions from a simple empirical model (3% of wind speed and turning angle 30°).

4.1 Comparison with the empirical model

Trajectories based on POM (including Stokes drift and tidal currents) and the empirical model are shown in Figure 10. The maximum wind speed for 23 October 2002 was 20.35 ms^{-1}.

As one can see from Figure 10, the empirical model provides a reasonable first estimate in areas where the mean current is small (drifter 17307) and gives worse results in the regions of strong currents (drifter 17306).

In addition, the empirical model trajectories lack the structure corresponding to tidal currents and inertial oscillations. This is further illustrated in Figure 11, where the forecast and empirical model trajectories are compared with the observed ones.

.

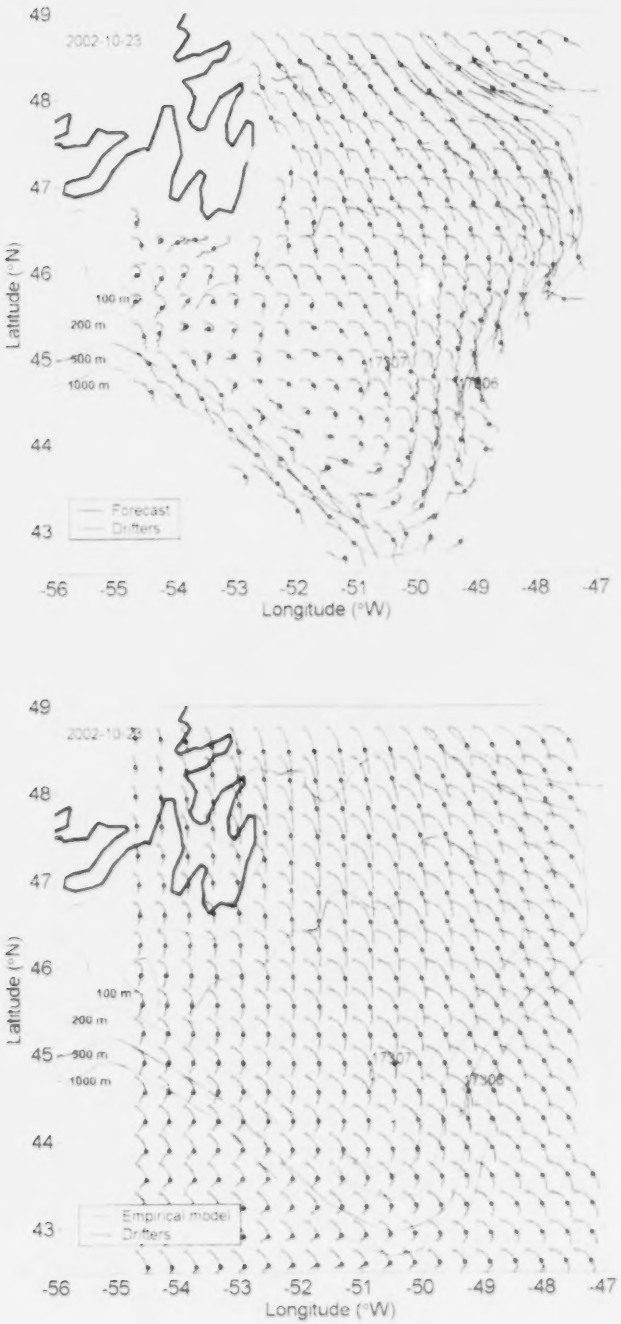


Figure 10. Comparison between POM (top) and simple wind based model (bottom) trajectories (blue). The observed drifter trajectories are plotted in red.

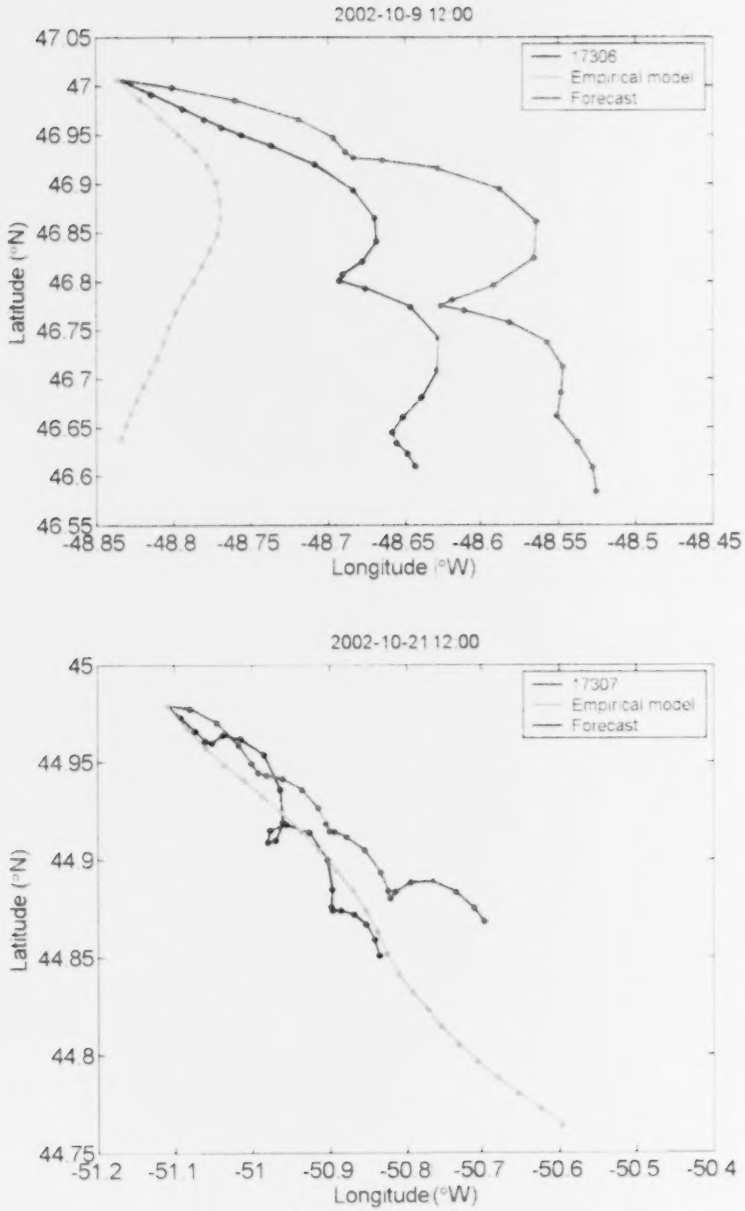


Figure 11. Comparison of the observed and modeled 2-day trajectory structure for two selected samples.

4.2 Comparison of time series

Current velocity components interpolated to drifter locations for the period when all four drifters were operating are shown in Figures 12 and 13. POM velocity components (that include the Stokes drift) correlate quite well with the drifter velocity components except few periods when the model exhibits large inertial oscillations. The empirical model does not include the tidal or inertial oscillatory velocity components.

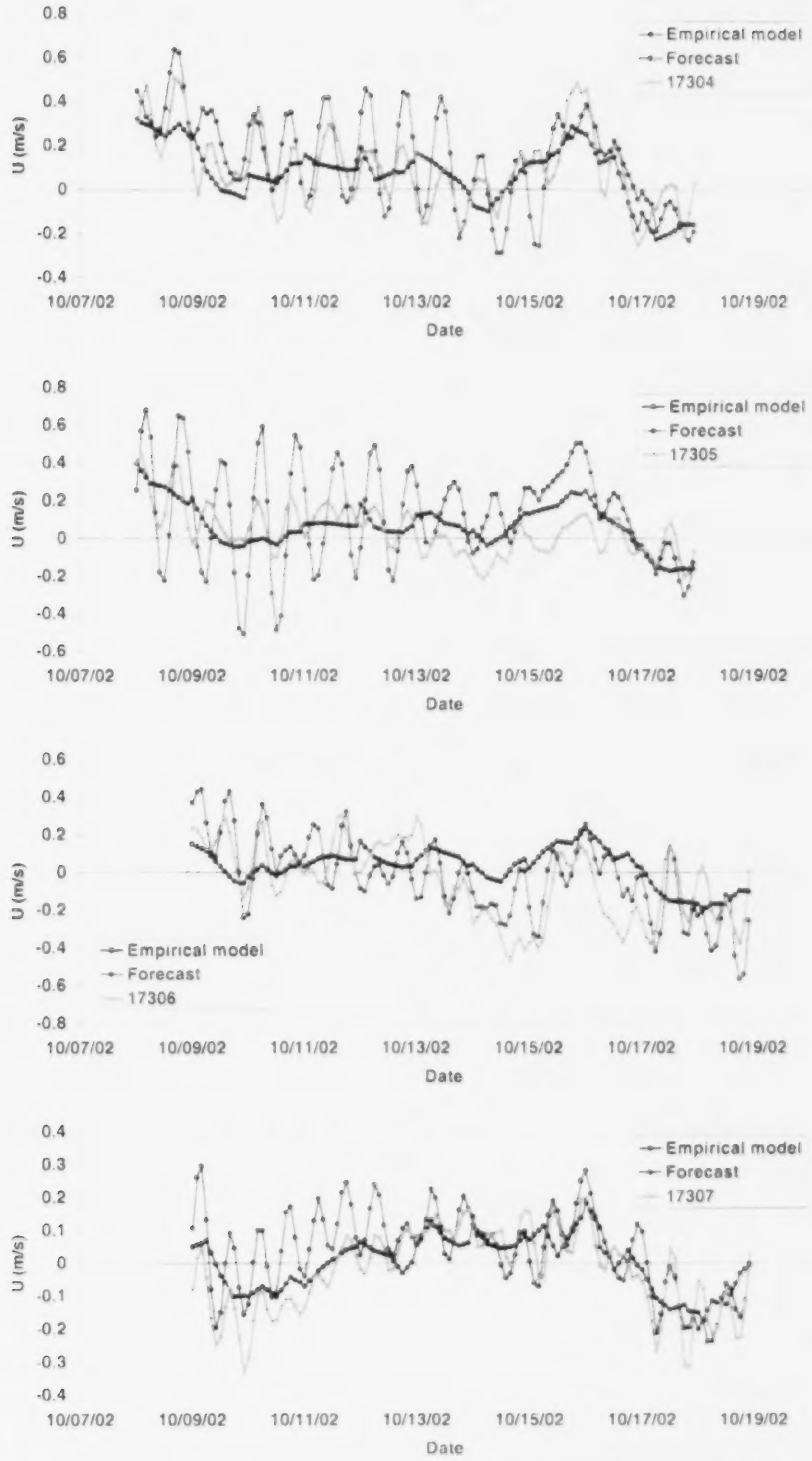


Figure 12. Comparison of drifter velocity component U (ms^{-1}) with modeled current velocity component U (ms^{-1}) at drifter locations

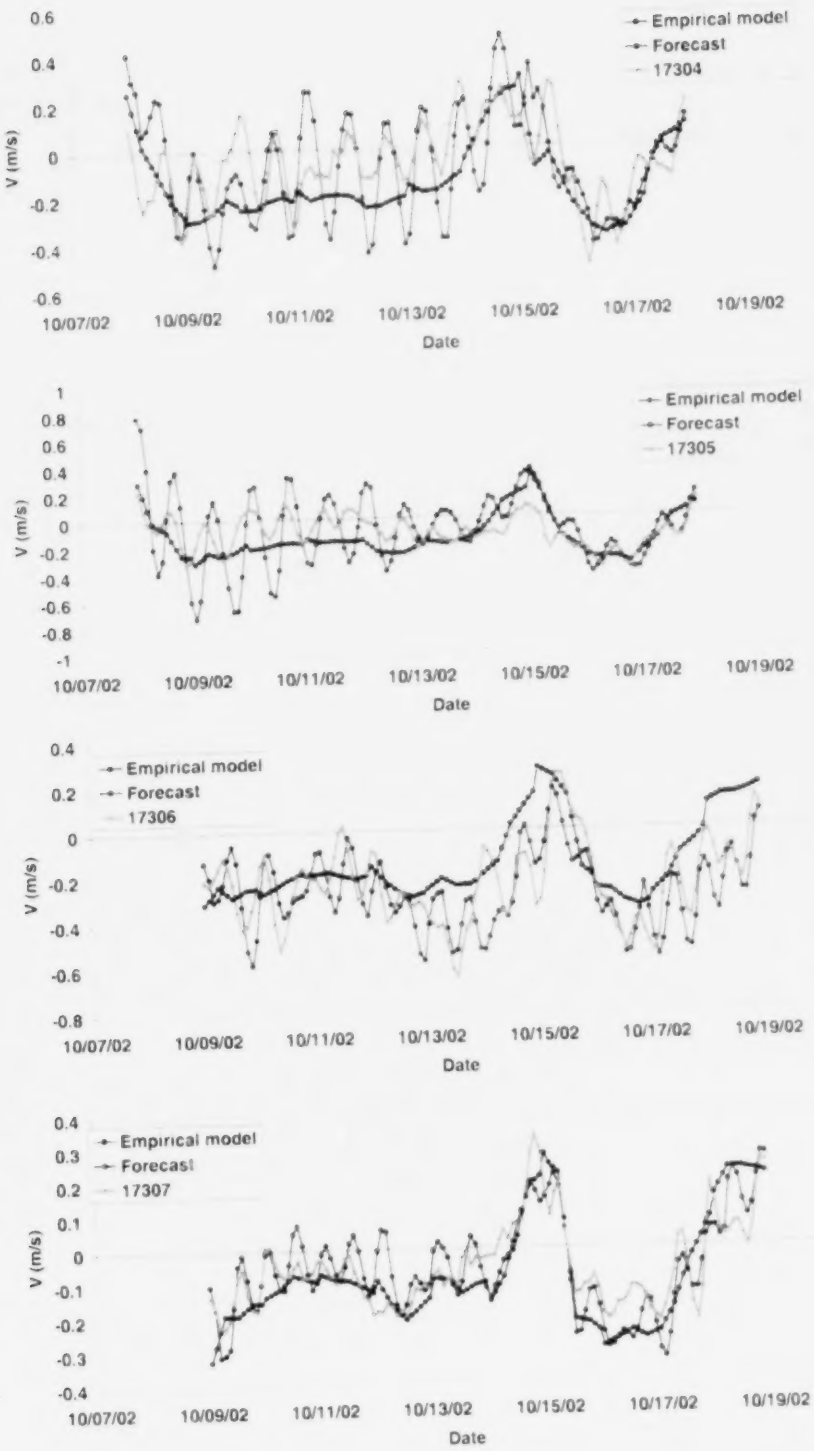


Figure 13. Comparison of drifter velocity component V (ms^{-1}) with modeled current velocity component V (ms^{-1}) at drifter locations

4.3 Comparison of trajectories

This section aims to quantify the deviation between the drifters and model trajectories. This is done by comparing the distances along trajectories and the separation between the trajectories after one and two days of forecast, as illustrated in Figure 14, for the entire period when the drifters were on the Grand Banks.

The scatter diagrams of the modeled distances on the observed ones are shown in Figure 15 for three cases: (1) POM without wave correction, (2) POM including Stokes drift and (3) empirical model. The separation between observed and modeled trajectories is indicated with the error-bar type lines. These lines are scaled by the factor of 0.2. Points corresponding to time lag of one day are plotted in green while data corresponding to time lag of two days are marked in blue. This data set contains 132 points.

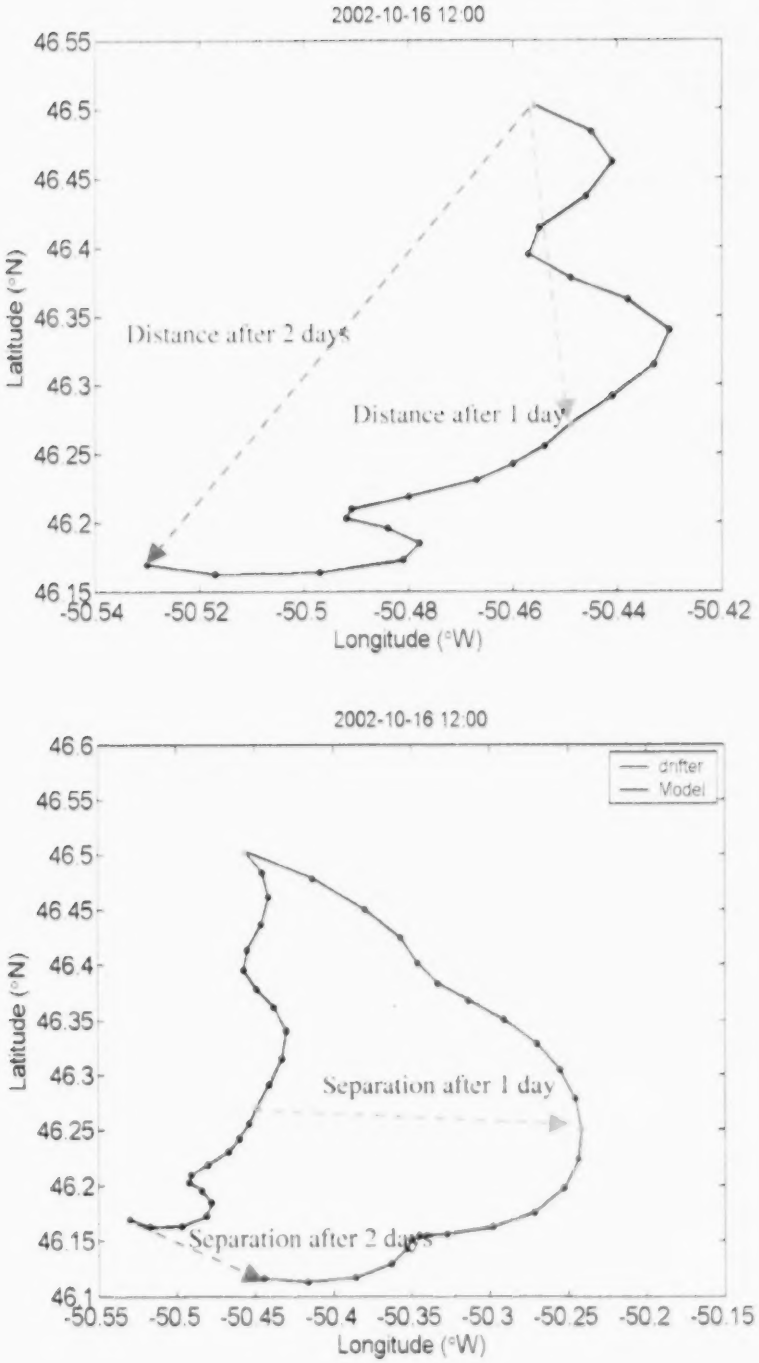


Figure 14. Diagram illustrating the distance (top) and separation (bottom) after 1 and 2 day

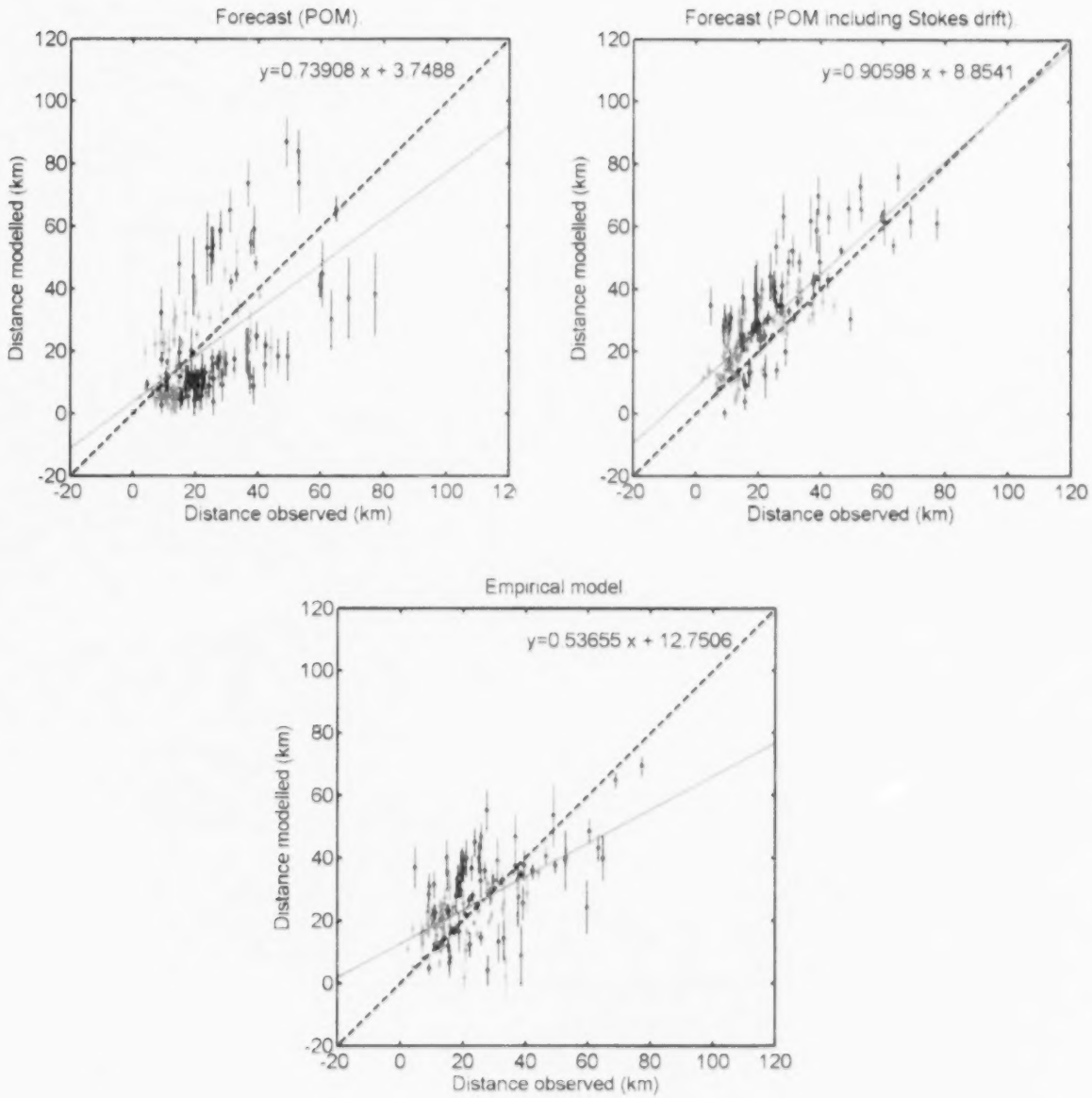


Figure 15. Scatter diagrams of the end points distance after 1 day (green dots) and 2 days (blue dots). The separation between the observed and modeled trajectories (indicated with vertical lines) is scaled by the factor 0.2. N=132 points. The red lines are linear fits of the data points.

Standard statistics for variable x are as follows:

$$Mean(x) = \frac{1}{N}\sum_{i=1}^{N} x_i$$

$$Std(x) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - Mean(x)\right)^2} = \sqrt{Var(x)}$$

$$Corr.Coeff(x, y) = \frac{Cov(x, y)}{\sqrt{Var(x)\cdot Var(y)}}$$

$$Cov(x) = \frac{1}{N}\sum_{i=1}^{N}\left(x_i - Mean(x)\right)\left(y_i - Mean(y)\right)$$

$$SI(x, y) = \frac{Std(x - y)}{Mean(x)}$$

The scatter index (SI) is defined as standard deviation divided by the average of observations. In this way the mean error has been eliminated. When the variability is great and the observation mean is low, the scatter index becomes large.

The mean and standard deviation of the separation between model and drifter trajectories after one and two days are summarized in Table 1. The correlation coefficient and scatter index of the trajectory distances after one and two days are given in Table 2.

Table 1 Separation mean ± standard deviation

N=132	**After 1 day (km)**	**After 2 days (km)**
POM	14.86 ± 8.39	26.29 ± 14.96
POM including Stokes drift	12.30 ± 6.22	20.38 ± 11.62
Empirical model	12.22 ± 7.17	21.11 ± 11.71

With the Stokes drift the mean separation is reduced from 15 km to 12 km after one day and from 26 km to 20 km after two days. Empirical model separation results are similar to those of the POM with Stokes drift included.

Table 2 Correlation coefficient and scatter index of the trajectory distance

N=132	Correlation Coefficient	Scatter Index (SI)
POM	0.58	0.67
POM including Stoke's drift	0.80	0.42
Empirical model	0.62	0.52

For distance, with the Stokes drift added to the POM results, the correlation between the distances along modeled and observed trajectories was increased by 0.22. In comparison to the empirical model results, the correlation was increased by 0.18. Similarly improvements are seen in the scatter index. Including Stokes drift in POM reduced the scattering by 0.25 for POM only and 0.10 for the empirical model.

These results are consistent with the graphical results presented in Sections 4.1 and 4.2. Considering the statistics for distance and separation as a whole (Tables 1 and 2), we conclude that surface currents generated from POM with the Stokes drift represent a real improvement over those from POM without the Stokes drift and from the empirial model.

5.0 Discussion

Current profile close to the surface in ocean models is sensitive to the way the eddy viscosity is specified or calculated. For a depth independent eddy viscosity, current velocity decreases exponentially with depth. In POM, the eddy viscosity in the top few meters increases linearly with depth, which gives rise to a logarithmic profile. This means, strictly speaking, velocity at the surface is not defined. In this study, we found that velocities at the first sigma level (approximately 1% of water depth) over-predict the surface velocities, and averaging of the velocities in the top 10 m or 30 m would give a better agreement with the observations. The reduction in current velocity by vertical averaging corrects for the high velocities very close to the surface in POM. The depth of averaging can be considered an adjustable parameter of the model. The root cause of the uncertainty is our poor knowledge of the spatial and temporal variations of the eddy viscosity. More efforts are needed to determine the most appropriete value and form of eddy viscosity. This is currently an area of active research. Recently, a formulation to modify the eddy viscosity to account for the effects of wave dissipation was proposed by Meller (2003), which should be tested using drifter data.

From the comparison of the modeled and observed velocities (Figs. 12 and 13), it is apparent that the inertial oscillations (period 16.4 hr) produced by the model are too large. Inertial currents are generated by wind forcing when the wind direction or speed change suddenly (DeYoung and Tang, 1990). The oscillations last for a short time, 3 to 6 days, due to friction. To reduce the magnitude of the inertial currents, enhanced damping in the upper layer is required in POM.

To include wave induced currents, a simple empirical equation for the Stokes drift, which requires only winds as input, was used in the simulations as a first-order approximation to the coupled wave-current response in this study. In order to correctly account for the wave effect on ocean currents, a fully coupled wave-ocean model is needed. Based on Jenkins' theory of the effect of waves on current velocities in the Ekman layer (Jenkins, 1987), a general formulation that incorporates the wave effects into the ocean model has been proposed by Perrie *et al.* (2003). According to this formulation, the Stokes drift is calculated from the two-dimensional energy spectrum of waves. Wind stress is partitioned between wave generation and current generation. Part of the wave momentum is transferred to the ocean through wave dissipation resulting in enhanced surface currents.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

- The agreement between the modeled and observed trajectories is reasonably good. The model surface currents include currents computed from POM and wave-induced Stokes drift. The Stokes drift is most important during high winds.
- The modeled surface current trajectories agree better with drifter data statistically and have more realistic structure (tidal currents, inertial oscillations) than the results based on an empirical model.
- The amplitudes of inertial oscillation in the model results exceed the observed values.
- POM's near-surface currents seem to be biased high without vertical averaging.
- Computation of trajectories may be sensitive to the velocity resolution (i.e. 2 hours in POM) as well as to other factors, e.g. the wind field spatial and temporal resolution. At present six hourly forecast winds are used.

Recommendations:

- Further model improvements are needed. These include coupling of wave and current dynamics, damping of inertial oscillations, and improved parameterization of the eddy viscosity.
- More drifter data should be acquired for model calibration and validation, especially data taken in winter when high wind conditions are more frequent.
- The model domain should be extended to cover a larger area including the Scotian Shelf, Baffin Bay and Gulf of St. Lawrence for a wider application.
- High-resolution wind data should be used.
- Other types of data useful for surface current research such as high-frequency radar data, which can provide continuous time series of surface velocity in a fixed area, should be investigated.

6.0 REFERENCES

Blumberg, A. F., and G.L. Mellor (1987). A description of a three-dimensional coastal ocean circulation model, in Three-Dimensional Coastal Ocean Models, Vol. 4, edited by N. Heaps, pp. 208, American Geophysical Union, Washington, D.C.

DeYoung, B. and C.L. Tang (1990). Storm-forced response of baroclinic near-inertial currents on the Grand Banks. Journal of Physical Oceanography, 20, 1725-1741.

Han, G. (2000). Three-dimensional modeling of tidal currents and mixing quantities over Newfoundland Shelf. Journal of Gephysical Research,105, 11407-11422.

Jenkins, A.D. (1987). Wind and wave induced currents in a rotating sea with depth varying eddy viscosity. Journal of Physical Oceanography, 17, 938-951.

Mellor, G.L. (1996). Users Guide for a Three-Dimensional, Primitive Equation, Numerical Ocean Model. Atmospheric and Oceanic Sciences Program, Princeton University, 40pp.

Mellor, G.L., and T. Yamada (1982). Development of a turbulence closure model for geophysical fluid problems, Review of Geophysics and Space Physics, 20, 851-875.

Mellor, G.L. (2003). The three-dimensional current and surface wave equations. Journal of Physical Oceanography, 33, 1978-1989.

Perrie, W., C. L. Tang, Y. Hu and B.M.De Tracy (2003). The impact of waves on surface currents. Journal of Physical Oceanography, 33, 2126-2140.

SEIMAC (2003). Self Locating Datum Marker Buoy (SLDMB) Reference Guide. March 15, 2004 (manual based on the National Defense Sonobuoy Reference Guide C-59-007-006/MB-001).

Wu, J. ((1983). Sea-surface drift currents induced by wind and waves. Journal of Physical Oceanography, 13, 1441-1451.

Yao, T., C.L. Tang and I.K. Peterson (2000). Modeling the seasonal variation of sea ice in the Labrador Sea with a coupled multi-category ice model and the Princeton Ocean Model. Journal of Geophysical Research, 105, 1153-1165.